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JRC Contribution to EVE IWG

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European Commission

Presentation Summary (1/2)

Follow-up of the JRC activities for contribution to the EVE IWG under the "in-vehicle battery ageing" topic

Summary after Geneva (Jan. 2018), i.e. what's old:

- Finalisation of the durability scenario analysis;
- In-vehicle cross-validation of the model's results against experimental data from Canada;

Presentation Summary (2/2)

Follow-up of the JRC activities for contribution to the EVE IWG under the "in-vehicle battery ageing" topic

Current Status (Mar. 2018), i.e. what's new:

- Scientific paper on battery durability submitted in Feb. 2018 to Applied Energy (to circulate as soon as it is accepted);
- Development of further scenarios for battery durability;

Performance based models (SotA)

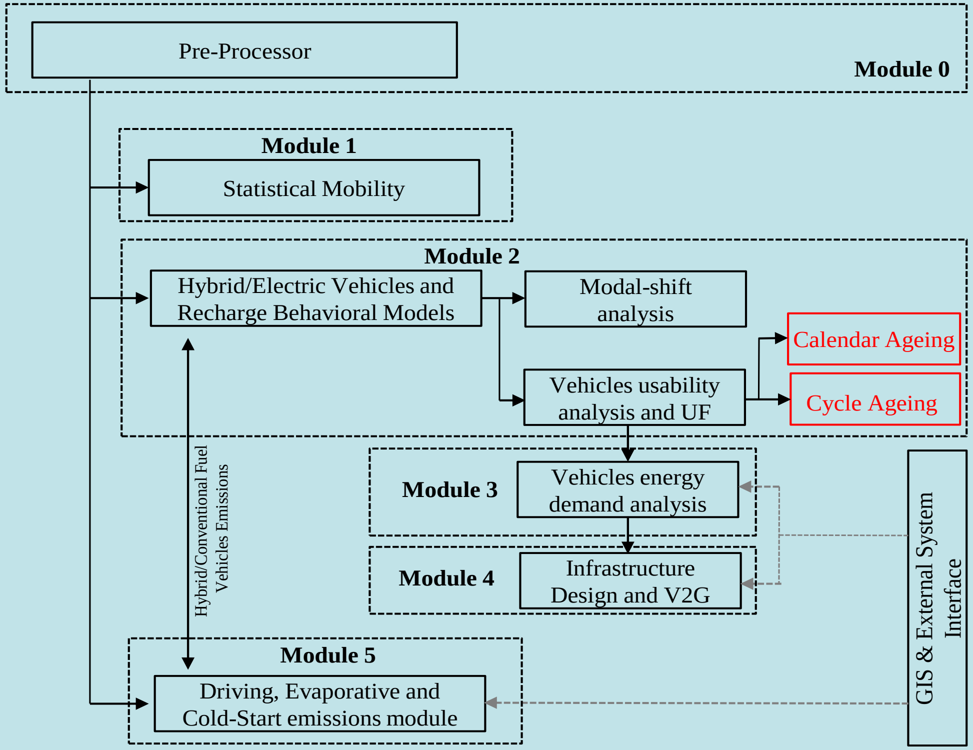
	Capacity fade		Power fade	
	Calendar	Cycle	Calendar	Cycle
$LiFePO_4$	Sarasketa-Zabala et Al. (2013/14);	Wang et Al. (2011); Sarasketa-Zabala et Al. (2013); Sarasketa-Zabala et Al. (2015);	Sarasketa-Zabala et Al. (2013);	
NCM + spinel Mn	Wang et Al. (2014);		-	-
NCM – LMO	-	Cordoba-Arenas et Al. (2014);	-	Cordoba-Arenas et Al. (2015);

Calendar + Cycle (4 Combinations):

- **#1 ($LiFePO_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Wang et Al. (2011) model for cycle;**
- **#2 ($LiFePO_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Sarasketa-Zabala et Al. (2015) model for cycle;**
- **#3 (NCM + Spinel Mn): Wang et Al. (2014) for calendar plus Wang et Al. (2014) for cycle;**
- **#4 (NCM-LMO): Wang et Al. (2014) for calendar plus Cordoba-Arenas et Al. (2015) for cycle;**

Implementation of the Performance based models into TEMA (assumptions, 1/2)

TEMA Structure



Vehicle Electric Architecture (examples)

PHEV

BEV 1

BEV 2

	Vehicle Type	Battery Size [Wh]	Battery Shape	No. of Cells [#] and Type	Reference Voltage [V]	Electric Architecture
T-Shaped	PHEV	16,000	T-shaped	192 – pouch	365	2P-96S
Parallelepiped	BEV 1	24,000	Parallelepiped	192 – pouch	360	48S-2P-2S
Flat-shaped	BEV 2	85,000	Flat	6,912 - cylindrical	345	16S-72P-6S

	Usable Energy at BoL [Wh]	Usable Energy at EoL [Wh]	Reserve [% of battery capacity]	Energy consumption [Wh/km]
T-shaped (PHEV)	12,000	9,600	25%	205
Parallelepiped (BEV 1)	18,000	14,400	15%	210
Flat-shaped (BEV 2)	63,750	51,000	15%	265

Implementation of the Performance based models into TEMA (assumptions, 2/2)

The models have been implemented by adopting the following assumptions:

- **the calendar and cycle capacity fades are calculated at cell level (uniform ageing assumption);**
- **the model assumes average quantities in the reference period per each vehicle for DOD, C-rate, Ah-throughput and temperature;**
- **DOD and temperature are assumed equal to the battery values, consistently with the uniform fade assumption, whilst the C-rate and Ah-throughput are scaled from the battery level down to the cell;**
- **the battery temperature is regulated by the BMS between 22 °C and 27 °C during the driving and recharging phases (cycle capacity fade modelling), whilst it assumes the ambient temperature in the parking phase (calendar capacity fade modelling);**
- **The model capacity fade is calculated at the net of the capacity fade reserve. i.e.:**

$$Q_{loss\text{-}total} = Q_{loss\text{-}calendar} + Q_{loss\text{-}cycle} - \text{Reserve}$$

- **5 recharge strategies adopted:**
  - ✓**Str. 1 = Long Stop Random AC;**
  - ✓**Str. 2 = Short-Stop Random DC;**
  - ✓**Str. 3 = Night AC - Str. 4 = Smart AC;**
  - ✓**Str. 5 = Long-Stop AC 3-phases;**

Results (Durability and EoL – tabulated)

Years of Life

					0 - 500 km/month: Years to EoL	0 - 500 km/month: Years to 100,000 km	500 – 1,000 km/month: Years to EoL	500 – 1,000 km/month: Years to 100,000 km	1,000 -1,500 km/month: Years to EoL	1,000 -1,500 km/month: Years to 100,000 km	1,500 – 2,000 km/month: Years to EoL	1,500 – 2,000 km/month: Years to 100,000 km	2,000+ km/month: Years to EoL	2,000+ km/month: Years to 100,000 km
Recharge Strategy #1	PHEV-1 5.8% fleet share	Ageing Model	#1	$LiFePO_4$	≥ 20	≥ 20	11.9	14.2	-		-		-	
			#2	$LiFePO_4$	17.0		6.1		-		-		-	
			#3	NCM-Mn	14.2		9.0		-		-		-	
			#4	NCM-LMO	16.5		14.6		-		-		-	
	BEV-1 12.1% fleet share		#1	$LiFePO_4$	13.5	≥ 20	6.6	12.8	4.7	7.9	-		-	
			#2	$LiFePO_4$	9.6		4.0		≤ 3.0		-		-	
			#3	NCM-Mn	8.5		5.8		4.6		-		-	
			#4	NCM-LMO	9.7		8.6		8.2		-		-	
	BEV-2 53.6% fleet share		#1	$LiFePO_4$	≥ 20	≥ 20	≥ 20	11.2	≥ 20	6.9	≥ 20	5.0	≥ 20	3.9
			#2	$LiFePO_4$	≥ 20		≥ 20		≥ 20		≥ 20		≥ 20	
			#3	NCM-Mn	12.6		13.4		14.2		15.0		16.0	
			#4	NCM-LMO	12.1		12.7		13.6		14.7		16.1	
Rech. Str. #2	BEV-1 24.8% fleet share	Ageing Model	#1	$LiFePO_4$	13.0	≥ 20	6.4	11.7	4.5	7.1	3.5	5.1	≤ 3.0	3.7
			#2	$LiFePO_4$	9.1		3.8		≤ 3.0		≤ 3.0		≤ 3.0	
			#3	NCM-Mn	7.9		5.2		3.9		3.1		≤ 3.0	
			#4	NCM-LMO	9.3		7.9		7.1		6.6		6.2	
	BEV-2 79.8% fleet share		#1	$LiFePO_4$	≥ 20	≥ 20	≥ 20	11.0	≥ 20	6.8	≥ 20	4.8	≥ 20	3.4
			#2	$LiFePO_4$	≥ 20		≥ 20		≥ 20		≥ 20		≥ 20	
			#3	NCM-Mn	12.1		11.9		11.8		11.6		11.3	
			#4	NCM-LMO	11.6		11.4		11.3		11.2		11.2	

Mileage @ EoL

					0 - 500 km/month	500 – 1,000 km/month	1,000 -1,500 km/month	1,500 – 2,000 km/month	2,000+ km/month
Recharge Strategy #1	PHEV-1 5.8% fleet share	Ageing Model	#1	$LiFePO_4$	56,947	83,657	-	-	-
			#2	$LiFePO_4$	≤ 50,000	≤ 50,000	-	-	-
			#3	NCM-Mn	≤ 50,000	63,270	-	-	-
			#4	NCM-LMO	≤ 50,000	102,638	-	-	-
	BEV-1 12.1% fleet share		#1	$LiFePO_4$	≤ 50,000	51,592	59,638	-	-
			#2	$LiFePO_4$	≤ 50,000	≤ 50,000	≤ 50,000	-	-
			#3	NCM-Mn	≤ 50,000	≤ 50,000	58,369	-	-
			#4	NCM-LMO	≤ 50,000	67,226	104,050	-	-
	BEV-2 53.6% fleet share		#1	$LiFePO_4$	157,504	≥300,000	≥300,000	≥300,000	≥300,000
			#2	$LiFePO_4$	176,336	≥300,000	≥300,000	≥300,000	≥300,000
			#3	NCM-Mn	≤ 50,000	120,037	205,502	297,360	≥300,000
			#4	NCM-LMO	≤ 50,000	113,767	196,819	291,413	≥300,000
Rech. Str. #2	BEV-1 24.8% fleet share	Ageing Model	#1	$LiFePO_4$	≤ 50,000	54,771	63,396	69,139	74,819
			#2	$LiFePO_4$	≤ 50,000	≤ 50,000	≤ 50,000	≤ 50,000	≤ 50,000
			#3	NCM-Mn	≤ 50,000	≤ 50,000	54,943	61,237	69,475
			#4	NCM-LMO	≤ 50,000	67,608	100,025	130,376	165,670
	BEV-2 79.8% fleet share		#1	$LiFePO_4$	147,804	≥300,000	≥300,000	≥300,000	≥300,000
			#2	$LiFePO_4$	171,195	≥300,000	≥300,000	≥300,000	≥300,000
			#3	NCM-Mn	≤ 50,000	107,766	174,392	239,644	≥300,000
			#4	NCM-LMO	≤ 50,000	103,238	167,003	231,381	≥300,000

Legend	
(red)	EoL below 5 years;
(yellow)	EoL between 5 and 10 years;
(green)	EoL above 10 years;

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Summary of the logical passages

#1

Performance-based models

(validated on exp. at cell-level)

#2

3 vehicle reference architectures

(from cell-to-vehicle)

#3

Real-world

Driving data

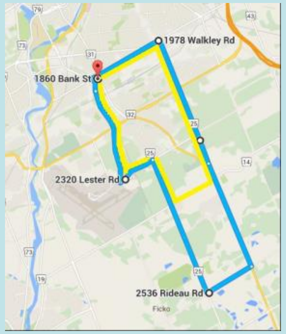
#4

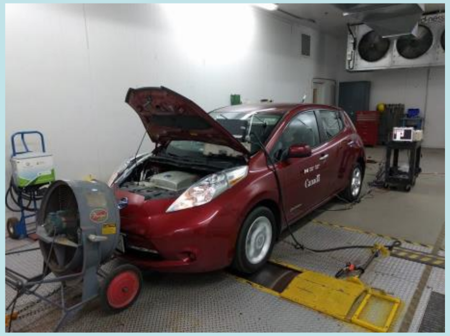
Durability Scenarios

(Yrs and/or km to EoL)

Experimental data from Canada (description)

	Test stage ID	Test-Type	Start Date	End Date	Recharge Level 2 [#]	Recharge Level 3 [#]	Average Recharging Power [kW]	Driven Distance [km]	Driving Time [h]	Recharging Time [h]	Resting Time [h]
Test vehicle #1 (manufact. 09/2014)	#1.1	In-Lab	05/03/2015	26/04/2015	26	-	4.2	3,021	50.9	115.8	1,081.3
	#1.2	On-Road	27/04/2015	30/08/2015	-	86	22.0	10,365	218.8	64.7	2,716.5
	#1.3	In-Lab	31/08/2015	14/09/2015	8	-	4.5	1,128	19.0	38.2	278.7
	#1.4	On-Road	15/09/2015	07/04/2016	-	240	14.9	18,683	397.5	214.9	4,307.6
	#1.5	In-Lab	08/04/2016	24/04/2016	17	-	3.9	1,339	22.9	50.9	310.3
	#1.6	On-Road	25/04/2016	24/10/2016	-	157	20.8	13,858	301.9	88.7	3,977.4
	#1.7	In-Lab	25/10/2016	04/11/2016	5	-	4.4	1,184	20.9	41.0	178.1
				Total (logged)	**483**	-	-	**49,578**	**1,031.8**	**614.2**	**12,849.9**
				Run-In (non-logged)	-	-	-	**1,663**	-	-	**4,384.8**
Test vehicle #2 (manufact. 11/2014)	#2.1	In-Lab	27/03/2015	10/05/2015	16	-	4.1	1,764	30.0	70.2	955.7
	#2.2	On-Road	11/05/2015	14/09/2015	118	-	4.3	10,971	224.2	333.2	2,466.6
	#2.3	In-Lab	15/09/2015	01/10/2015	11	-	4.1	1,298	22.7	50.3	311.0
	#2.4	On-Road	02/10/2015	08/05/2016	241	-	4.5	18,716	364.8	700.3	4,190.9
	#2.5	In-Lab	09/05/2016	29/05/2016	10	-	4.1	1,311	22.8	46.1	411.1
	#2.6	On-Road	30/05/2016	08/11/2016	143	-	4.2	12,770	271.2	385.7	3,231.0
	#2.7	In-Lab	09/11/2016	23/11/2016	14	-	4.2	1,334	22.5	46.7	266.7
				Total (logged)	**553**	-	-	**48,164**	**958.2**	**1,632.7**	**11,833.1**
				Run-In (non-logged)	-	-	-	**2,214**	-	-	**3,384.9**





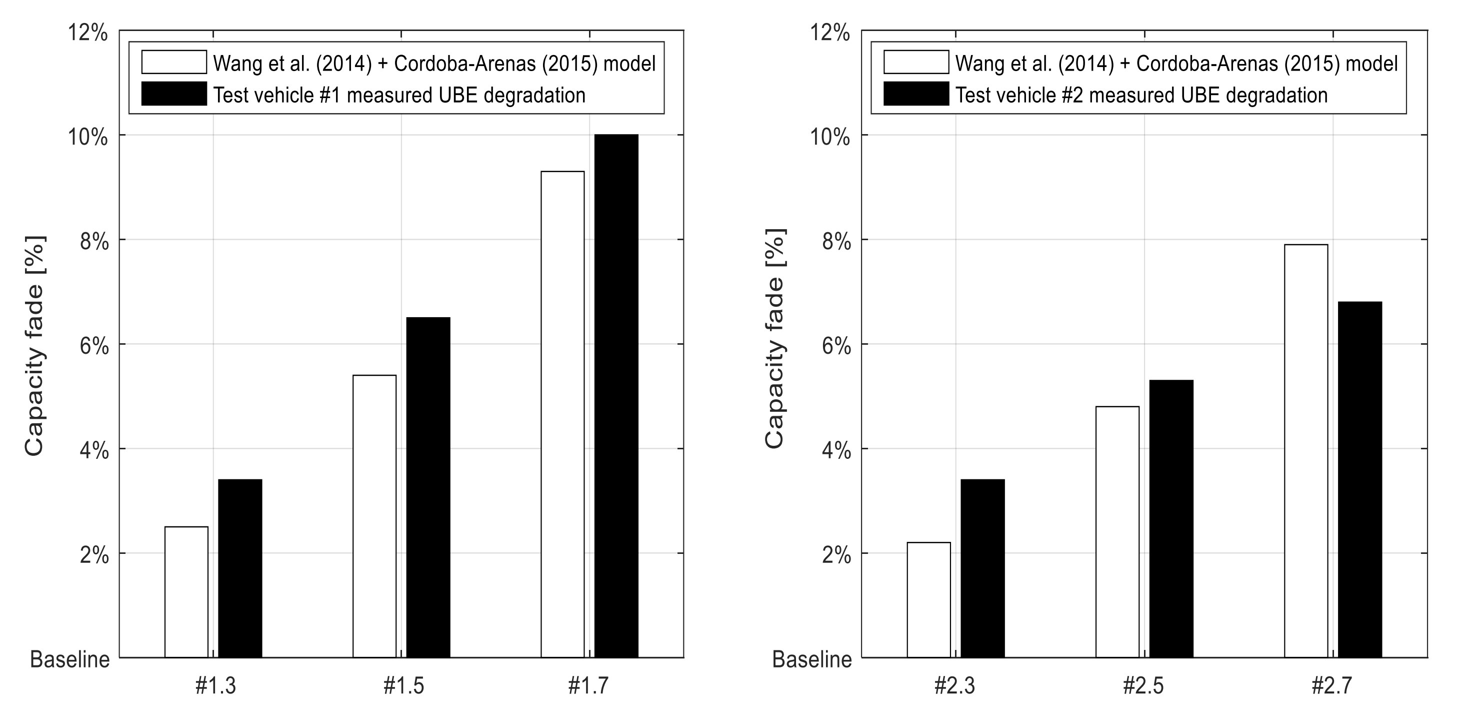
	Test stage ID	Test-Type	Aver. weighted battery temperature [K]	Average air temperature [K]	Average weighted C-rate	Battery Ah-throughput [Ah]	SoC_{min} [%]	UBE degradation since stage x.1 [%]	Odometer reading [km]	Age of the car since manufacture [yrs]
Test vehicle #1 (manufact. 09/2014)	#1.1	In-Lab	288.9	284.9	0.31	2,672.8	7.7	**0.0%**		
	#1.2	On-Road	300.8	291.0	0.44	8,655.9	42.5			
	#1.3	In-Lab	304.1	300.4	0.32	987.6	4.6	**-3.4%**	**16,177**	**1.04**
	#1.4	On-Road	287.7	274.9	0.43	18,630.8	41.6			
	#1.5	In-Lab	298.0	297.2	0.29	1,127.7	12.0	**-6.5%**	**36,199**	**1.65**
	#1.6	On-Road	297.8	290.2	0.48	11,317.4	39.7			
	#1.7	In-Lab	303.0	297.6	0.31	1,018.0	10.2	**-10.0%**	**51,241**	**2.18**
Test vehicle #2 (manufact. 11/2014)	#2.1	In-Lab	286.8	283.8	0.33	1,626.2	7.5	**0.0%**		
	#2.2	On-Road	299.5	292.6	0.22	8,970.5	37.6			
	#2.3	In-Lab	296.4	291.9	0.33	1,200.3	4.9	**-3.4%**	**16,247**	**0.92**
	#2.4	On-Road	282.3	277.3	0.25	18,391.2	36.2			
	#2.5	In-Lab	301.1	296.7	0.32	1,117.4	8.7	**-5.3%**	**36,247**	**1.58**
	#2.6	On-Road	295.9	286.4	0.22	10,433.5	41.1			
	#2.7	In-Lab	302.2	298.9	0.32	1,143.1	7.3	**-6.8%**	**50,378**	**2.06**

Source: Presentation from Transport Canada @ EVE-22 (Ann-Arbor, April 2017)

Experimental data from Canada (Validation)

In-vehicle validation of the models (assumptions):

- **Uniform T, DoD, C-rate and Ah-throughput;**
- **T, DoD @ battery level;**
- **C-rate and Ah-throughput @ cell level;**
- $Q_{loss\text{-}total} = Q_{loss\text{-}cal.} + Q_{loss\text{-}cycle}$ **- Reserve(10%);**
- **NCM-LMO model (closer to real LEAF chemistry i.e. $LiMn_2O_4$ with $LiNiO_2$)**



The results will be described in the scientific paper:
"Capacity fade of Lithium-ion automotive batteries under real-world use conditions", Submitted in Feb. 2018.

Further Scenarios explored

New scenarios include:

- **Additional database included in the analysis on 61 pilot scenarios → deviation < 3.2%**
- **2 additional vehicles (i.e. A-segment vehicle + D-segment SUV):**
  - **Focus on NCM-LMO chemistry;**
  - **5 recharge strategies per 5 user bins (as above);**
  - **Estimation of the Years needed to reach 90% - 80% - 70% - 60% - 50% capacity fade;**

Further Scenarios explored

Modena Database Li-Ion NCM-LMO (2015) Years Driving to Set Threshold			0-500 km/month					500-1000 km/month					1000-1500 km/month					1500-2000 km/month					> 2000 km/month				
			90%	80%	70%	60%	50%	90%	80%	70%	60%	50%	90%	80%	70%	60%	50%	90%	80%	70%	60%	50%	90%	80%	70%	60%	50%
Long Stop Random AC	Vehicle-Type	A-segment	4.6	9.0	14.9	20-25	>25	3.8	7.4	12.3	18.5	>25			n.a.					n.a.					n.a.		
		BEV-1	4.9	9.7	16	20-25	>25	4.4	8.6	14.3	20-25	>25	4.2	8.2	13.7	20-25	>25			n.a.					n.a.		
		BEV-2	6.2	12.1	20	>25	>25	6.5	12.7	20-25	>25	>25	6.9	13.6	20-25	>25	>25	7.5	14.7	20-25	>25	>25	8.2	16.1	>25	>25	>25
		D-segment(SUV)	6.2	12.1	20	>25	>25	6.5	12.9	20-25	>25	>25	7.1	13.9	20-25	>25	>25	7.7	15.0	20-25	>25	>25	8.6	16.8	>25	>25	>25
		PHEV-1	3.2	7.3	13	20-25	>25	2.8	6.4	11.5	18	>25			n.a.					n.a.					n.a.		
Short Stop Random DC	Vehicle-Type	A-segment	4.4	8.6	14.2	20-25	>25	3.5	6.8	11.4	17.1	20-25	3	6.0	10.0	14.9	20-25	2.7	5.3	8.9	13.4	18.8			n.a,		
		BEV-1	4.7	9.3	15.4	20-25	>25	4	7.9	13.1	19.6	>25	3.6	7.1	11.8	17.8	20-25	3.4	6.6	11.0	16.6	20-25	3.1	6.2	10.2	15.4	20-25
		BEV-2	5.9	11.6	19.2	>25	>25	5.8	11.4	18.8	>25	>25	5.7	11.3	18.6	>25	>25	5.7	11.2	18.6	>25	>25	5.7	11.2	18.5	>25	>25
		D-segment(SUV)	5.9	11.6	19.1	>25	>25	5.8	11.3	18.7	>25	>25	5.7	11.2	18.5	>25	>25	5.7	11.1	18.4	>25	>25	5.7	11.1	18.4	>25	>25
		PHEV-1			n.a.					n.a.					n.a.					n.a.					n.a.		
Night AC	Vehicle-Type	A-segment	4.5	8.8	14.5	20-25	>25	3.7	7.3	12.1	18.2	>25	3.4	6.7	11.2	16.8	20-25			n.a.					n.a.		
		BEV-1	4.9	9.6	15.8	20-25	>25	4.3	8.5	14.2	20-25	>25	4.1	8.2	13.6	20-25	>25	4.1	8.0	13.3	20.0	>25			n.a.		
		BEV-2	6.2	12.1	20.0	>25	>25	6.5	12.7	20-25	>25	>25	7.0	13.7	20-25	>25	>25	7.5	14.8	20-25	>25	>25	8.1	16.0	>25	>25	>25
		D-segment(SUV)	6.2	12.1	20.0	>25	>25	6.6	12.9	20-25	>25	>25	7.1	13.9	20-25	>25	>25	7.7	15.2	>25	>25	>25	8.3	16.2	>25	>25	>25
		PHEV-1	3.2	7.1	12.7	19.9	>25	2.8	6.3	11.3	17.8	>25	2.7	6.0	10.8	17.0	20-25			n.a.					n.a.		
Smart AC	Vehicle-Type	A-segment	4.5	8.8	14.6	20-25	>25	3.7	7.3	12.2	18.3	>25	3.4	6.7	11.1	16.7	20-25			n.a.					n.a.		
		BEV-1	4.9	9.6	15.9	20-25	>25	4.3	8.6	14.2	20-25	>25	4.2	8.2	13.6	20-25	>25			n.a.					n.a.		
		BEV-2	6.1	12.1	19.9	>25	>25	6.5	12.7	20-25	>25	>25	6.7	13.1	20-25	>25	>25			n.a.					n.a.		
		D-segment(SUV)	6.2	12.1	20.0	>25	>25	6.5	12.8	20-25	>25	>25	6.7	13.1	20-25	>25	>25			n.a.					n.a.		
		PHEV-1	3.2	7.2	12.8	20	>25	2.8	6.4	11.4	17.9	>25			n.a.					n.a.					n.a.		
Long Stop AC 3-phases	Vehicle-Type	A-segment	4.3	8.5	14.1	20-25	>25	3.4	6.8	11.3	17.0	20-25	3	6.0	10.0	15.0	20-25	2.8	5.4	9.1	13.6	20-25	2.5	5.0	8.4	12.6	17.7
		BEV-1	4.7	9.3	15.4	20-25	>25	4	7.9	13.2	19.7	>25	3.7	7.2	12.0	18.0	>25	3.4	6.8	11.2	16.9	20-25	3.2	6.3	10.5	15.7	20-25
		BEV-2	6.0	11.7	19.3	>25	>25	5.9	11.6	19.2	>25	>25	5.9	11.6	19.3	>25	>25	6.0	11.7	19.4	>25	>25	6.1	12.0	19.9	>25	>25
		D-segment(SUV)	5.9	11.7	19.3	>25	>25	5.9	11.6	19.2	>25	>25	5.9	11.6	19.2	>25	>25	6.0	11.7	19.4	>25	>25	6.1	12.0	19.9	>25	>25
		PHEV-1	3.1	6.9	12.3	19.3	>25	2.6	5.9	10.5	16.5	20-25	2.4	5.4	9.6	15.0	20-25	2.2	5.0	8.9	14.0	20-25	2.1	4.7	8.5	13.3	19.3

Legend	
(red)	EoL below 5 years;
(yellow)	EoL between 5 and 10 years;
(green)	EoL above 10 years;

Thank you for the attention

Q&A

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